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Experimental Performance Comparison of Hierarchical Multi-Hub and Single-Hop Multi-Node LoRa Networks Using Sequential Polling

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ABSTRACT

LoRa networks commonly employ direct single-hop communication between end devices and a gateway; however, this architecture depends on reliable gateway connectivity for every node. A hierarchical multi-hub architecture provides an intermediate data collection layer but introduces additional communication transactions. This study experimentally compares hierarchical multi-hub and single-hop multi-node LoRa architectures using sequential polling under equivalent report-source counts. Four configurations were evaluated: A1 and A2 represented multi-hub communication with two and four report sources, respectively, while B1 and B2 represented equivalent single-hop multi-node configurations. Each configuration was tested for 30 rounds at distances of 10, 50, and 100 m using identical radio parameters. Performance was evaluated using report delivery ratio (PDR), gateway-facing received signal strength indicator (RSSI), round completion time, timeout events, and successful-round ratio. All configurations achieved a PDR of 100% at every distance. A1, B1, and B2 completed all rounds successfully, whereas A2 achieved a successful-round ratio of 96.67% because one timeout occurred at each distance. The mean round completion times were 4.211–4.228 s for A1, 9.208–9.253 s for A2, 1.970–1.974 s for B1, and 3.889–3.897 s for B2. Gateway-facing RSSI decreased with distance, but this reduction did not cause report loss within the tested range. These results demonstrate that single-hop multi-node communication provides faster data collection when direct links are reliable, whereas multi-hub communication provides a structured hierarchical collection path at the cost of higher round completion time.

INTRODUCTION

The rapid development of the Internet of Things (IoT) has increased the demand for wireless communication systems capable of collecting data from distributed field devices in a reliable, coordinated, and efficient manner. Long Range (LoRa) technology has been widely adopted in IoT applications because it provides wide communication coverage with relatively low power consumption. These characteristics make LoRa suitable for environmental monitoring, smart agriculture, infrastructure monitoring, and distributed data collection. However, as the number of devices increases, message exchanges may become less coordinated, particularly when multiple nodes operate on the same communication channel. Unscheduled transmissions may increase the probability of packet collisions, packet loss, and delay variation (Sun et al., 2022; Li & Cao, 2022; Banti et al., 2022).

Scheduled communication provides an alternative approach for controlling device access to a shared LoRa channel. In a polling-based mechanism, a device transmits its data only after receiving a request from the network controller. This approach reduces the probability of simultaneous transmissions and provides a more deterministic data collection process. Previous studies have shown that time-slotted, Time Division Multiple Access (TDMA), and real-time communication mechanisms can improve the coordination and reliability of LoRa communications (Alahmadi et al., 2022; Fahmida et al., 2024; Beletsioti et al., 2025; Sahoo et al., 2025). A previous study introduced Gateway-Polled Sequential Access (GPSA), in which the gateway sequentially polls each node. Experimental evaluation demonstrated that GPSA could provide controlled data collection in a single-hop multi-node LoRa network (Ridho et al., 2025).

Although a single-hop multi-node architecture is relatively simple, every node must establish a direct communication link with the gateway. This requirement may become restrictive when nodes are deployed over a wide area, obstructed by physical objects, or located in areas with uneven signal quality. Deploying additional gateways can address some coverage limitations, but it also increases hardware and infrastructure requirements. An alternative approach is to introduce an intermediate hub or relay layer. In this hierarchical architecture, a node transmits its data to an associated hub, which subsequently forwards the data to the gateway. The intermediate layer reduces the dependence of end nodes on direct gateway connectivity and provides a structural basis for data collection in more complex deployment environments (Wong et al., 2024; Strzoda & Grochla, 2024).

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The use of intermediate hubs introduces additional communication overhead. Node-to-hub and hub-to-gateway transactions require additional transmissions, waiting periods, and processing activities within each data collection cycle. Consequently, a hierarchical multi-hub architecture may require a longer round completion time than a single-hop multi-node architecture. Previous studies have investigated relay-assisted and multi-hop LoRa communications as solutions to direct-link limitations. However, these studies have mainly focused on routing strategies, relay selection, energy consumption, large-scale simulations, or application-specific deployments (Osorio et al., 2022; Alhomyani et al., 2024; García et al., 2025).

This study experimentally compares the performance of hierarchical multi-hub and single-hop multi-node LoRa architectures using sequentially controlled data collection. The comparison considers two network-load levels, consisting of two and four report sources, at test distances of 10, 50, and 100 m. System performance is evaluated using the report delivery ratio (PDR), received signal strength indicator (RSSI) of gateway-facing links, round completion time, timeout events, and successful-round ratio. The study addresses how the network architecture affects report delivery reliability and data collection time, as well as how increasing distance affects the quality of links to the gateway. The main contribution is a controlled experimental comparison between direct and hierarchical LoRa data collection under equivalent test conditions. This comparison provides measurable evidence of the trade-off between the lower collection time of direct single-hop communication and the additional communication overhead required to support a hierarchical hub-based structure.

LITERATURE REVIEW

LoRaWAN commonly adopts a star-of-stars architecture in which end devices communicate directly with one or more gateways. This architecture is relatively simple because it does not require packet routing or forwarding among end devices. However, communication performance depends on the ability of each device to establish a direct link with a gateway. Network performance may also decrease when the number of devices or offered traffic increases, particularly when channel access is not sufficiently coordinated. The surveys conducted by Sun et al. (2022) and Li and Cao (2022) indicate that LoRa network scalability is affected by radio configuration, device population, traffic patterns, collision probability, and channel access mechanisms. From an energy-efficiency perspective, Banti et al. (2022) further explain that network performance is determined not only by physical communication range but also by communication protocols, retransmissions, and device energy consumption.

Several scheduled communication mechanisms have been developed to improve the deterministic behavior of LoRa networks. Alahmadi et al. (2022) proposed a time-slotted LoRa MAC protocol to improve network scalability and reduce the probability of packet collisions. Adaptive MAC mechanisms have also been developed for event-response applications, in which coordinated channel access is required to maintain reliable communication during sudden increases in network traffic (Asteriou et al., 2022). Similarly, DSME-LoRa adapts scheduled communication to coordinate transmissions among resource-constrained LoRa devices (Álamos et al., 2022). Fahmida et al. (2024) introduced a real-time communication protocol designed to provide more predictable packet delivery times, while LoRaHART incorporates hardware characteristics into real-time transmission scheduling (Sahoo et al., 2025). Beletsioti et al. (2025) proposed a gateway-controlled TDMA mechanism that also considers gateway energy consumption. Collectively, these studies demonstrate that scheduled channel access can reduce transmission uncertainty. Nevertheless, their primary focus is on MAC-layer scheduling rather than a controlled comparison between direct single-hop and hierarchical data collection architectures.

Multi-hop, mesh, and relay-assisted communications have been investigated to reduce the dependence of end devices on direct gateway connectivity. Wong et al. (2024) classified recent multi-hop and mesh LoRa approaches and showed that intermediate forwarding devices can improve topology flexibility and support communication in areas that are difficult to reach through a direct gateway link. However, additional hops also introduce end-to-end delay, relay energy consumption, coordination requirements, and greater network complexity. Multi-hop communication is therefore not inherently superior to single-hop communication under all operating conditions. Its suitability depends on direct-link quality, network size, forwarding strategy, traffic requirements, and acceptable delay.

Experimental evidence concerning multi-hop LoRa communication under non-line-of-sight (NLOS) conditions was presented by Osorio et al. (2022). Their study implemented a gossip-based routing mechanism in a university campus environment where direct LoRaWAN communication was affected by physical obstacles. The results showed that packet delivery to the gateway increased from 0% under the tested direct LoRaWAN conditions to at least 53% when multi-hop routing was applied. These results provide experimental evidence that intermediate forwarding can support data delivery when direct gateway connectivity is severely degraded. However, because the proposed system employed gossip-based routing rather than a predefined gateway–hub–node architecture, it did not quantify the round-time overhead of sequential hierarchical data collection.

Relay selection was investigated from a different perspective by Strzoda and Grochla (2024). They proposed an energy-efficient relay selection method for Low-Power Wide-Area Networks to address coverage blind spots and poor direct connectivity. Their approach considered radio coverage, spreading factor, and the energy budget of relay devices. The evaluation was conducted through large-scale simulations involving multiple gateways and large device

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populations. Consequently, the study is useful for explaining the role of relays in extending connectivity, but it does not quantify the round-time overhead of a small hierarchical testbed with sequentially controlled communication.

A more direct comparison between single-hop and multi-hop LoRaWAN was conducted by Alhomyani et al. (2024) using an analytical model for a linear pipeline-monitoring network. Their model evaluated network capacity, throughput, payload size, and energy consumption under single-hop and several multi-hop configurations. The results indicated that multi-hop deployment could improve throughput and support a larger linear deployment area. However, forwarding packets through intermediate sensors also increased network traffic and could contribute to congestion as the traffic load increased. Because the evaluation was analytical and application-specific, it did not directly examine PDR, gateway-facing RSSI, timeout events, or complete round duration in a physical testbed. The study therefore provides theoretical evidence of the trade-off between single-hop and multi-hop operation but leaves a need for controlled experimental comparison.

García et al. (2025) developed a LoRaWAN proof-of-concept that supports the coexistence of star single-hop and mesh multi-hop topologies. Their system dynamically selected the communication topology based on physical link-quality indicators. Experimental tests demonstrated successful topology switching and reported latency values between 0.5 and 3.2 s, together with changes in RSSI and signal-to-noise ratio. This work is closely related to the comparison of direct and hierarchical communications because it evaluates both communication modes using physical devices. However, its adaptive topology manager, LoRaWAN operation, and mesh-forwarding procedure differ from a predefined gateway–hub–node architecture controlled through sequential polling. The results therefore cannot be compared numerically without considering differences in protocol operation, radio parameters, network size, and latency definition.

In previous work, Ridho et al. (2025) introduced Gateway-Polled Sequential Access (GPSA) for a single-hop multi-node LoRa network. In GPSA, the gateway sequentially polls each node, allowing the nodes to transmit only after receiving a request. This controlled mechanism provides the basis for extending gateway polling to a hierarchical architecture. In hierarchical gateway-polled communication, the gateway polls each hub, while each hub collects data from its associated node before forwarding the reports to the gateway. Preliminary multi-hub evaluation showed that sequential hub polling could provide structured data collection. However, that evaluation focused on selecting a suitable communication mechanism within the multi-hub architecture and did not directly compare multi-hub and multi-node configurations with equivalent report-source counts and test conditions.

The reviewed studies reveal two principal architectural trade-offs. Single-hop communication provides a simpler transaction path and avoids intermediate forwarding, but it requires every end device to maintain direct gateway connectivity. Hierarchical or multi-hop communication introduces hubs or relays that can support data forwarding when direct connectivity is inadequate, but each additional communication stage increases processing, waiting, and transmission overhead. Existing studies have generally evaluated these architectures separately or through analytical models, large-scale simulations, adaptive mesh mechanisms, or combined relay-and-retransmission schemes. A controlled physical comparison using the same radio configuration, communication distance, number of report sources, number of rounds, and sequential access principle remains limited. This gap motivates the experimental comparison of hierarchical multi-hub and single-hop multi-node LoRa architectures presented in this study.

METHOD

Research Design

This study employed a comparative experimental method to evaluate two LoRa communication architectures: hierarchical multi-hub and single-hop multi-node. Both architectures used sequential access controlled by the gateway. In the multi-hub architecture, data collection involved two communication levels, namely node-to-hub and hub-to-gateway. In the multi-node architecture, all report sources communicated directly with the gateway. This design was used to examine the effects of communication architecture on report delivery reliability, gateway-facing link quality, and data collection round completion time.

The comparison was designed using equivalent numbers of report sources. Scenario A1 was compared with B1 because both involved two report sources, whereas A2 was compared with B2 because both involved four report sources. This paired design allowed the architectures to be compared at equivalent offered report loads.

Communication Architectures

The hierarchical multi-hub architecture consisted of a gateway, one or more hubs, and associated nodes. The gateway served as the communication controller and central data logger. Each hub acted as a local data collector that received a report from its associated node and forwarded the collected data to the gateway. The node operated as the report source at the lowest level of the hierarchy and did not communicate directly with the gateway.

During each round, the gateway sequentially polled the hubs. After receiving a gateway request, a hub requested data from its associated node. The node transmitted its report to the hub, after which the hub transmitted its own report and the associated node report to the gateway. The gateway recorded the completion status after all hubs had been processed. This hierarchical polling procedure was applied in A1 and A2.

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The single-hop multi-node architecture consisted of one central gateway and multiple report sources. Each source communicated directly with the gateway without an intermediate forwarding device. The gateway sequentially polled the sources and recorded every received report. After all sources had been processed, the gateway recorded the round completion time and status. This procedure was applied in B1 and B2. The sequential access mechanism was adapted from the Gateway-Polled Sequential Access approach previously evaluated in a single-hop multi-node LoRa network (Ridho et al., 2025).

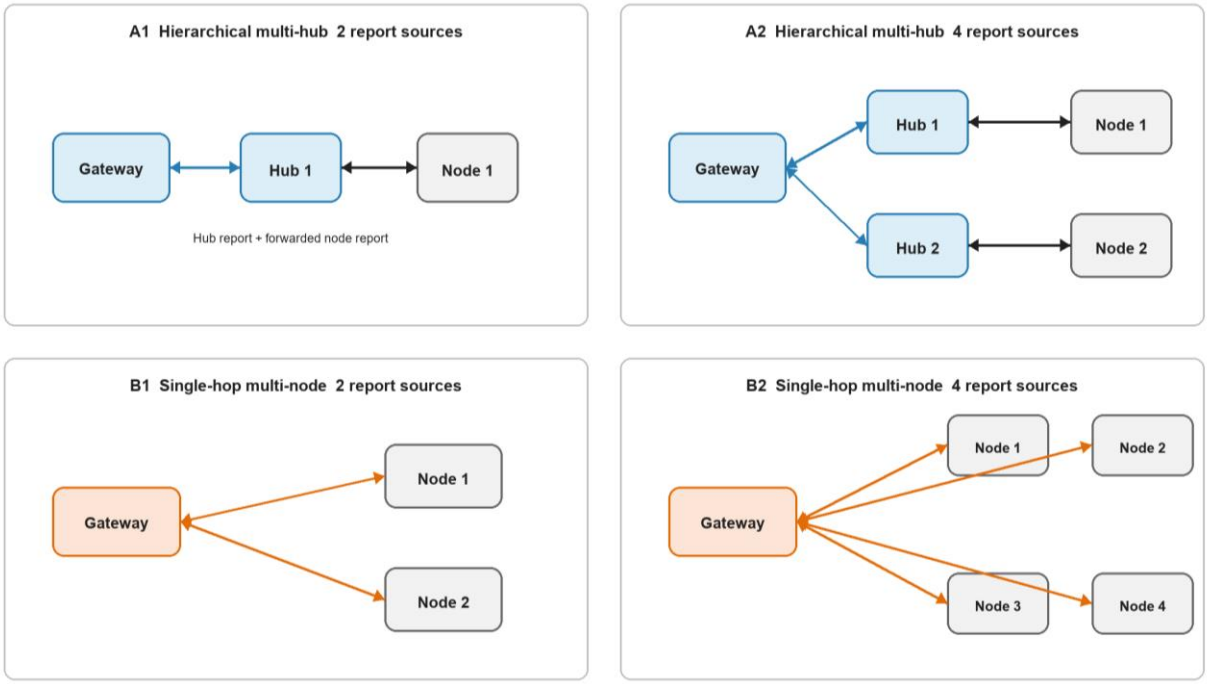


Figure 1. Hierarchical multi-hub and single-hop multi-node communication architectures

Hardware and LoRa Configuration

Each device was built using an ESP32 microcontroller and an Ebyte E220-900T22D LoRa module. The gateway was equipped with a MicroSD module to store the experimental records in comma-separated values (CSV) format. The same radio channel and communication parameters were used in all scenarios to maintain consistent experimental conditions.

The LoRa modules operated in fixed transmission mode, in which each message was transmitted using the address of the intended destination. The modules were configured on channel 71 at 921.5 MHz, with an air data rate of 2.4 kbps and an output power of 22 dBm. Packet RSSI and channel RSSI were enabled to allow received signal strength values to be read and recorded. Listen Before Talk was disabled because channel access was controlled by the polling mechanism. The principal hardware and radio configurations are presented in Table 1.

Table 1. LoRa hardware and communication configuration

Parameter	Configuration
Microcontroller	ESP32
LoRa module	Ebyte E220-900T22D
Transmission mode	Fixed transmission
Serial baud rate	9600 bps
Air data rate	2.4 kbps
Channel/ Frequency	71/921.5 MHz
Output power	22 dBm
Sub-packet length	200 bytes
Packet RSSI	Enabled
Channel RSSI	Enabled
Listen Before Talk	Disabled

Experimental Scenarios

Four experimental scenarios were evaluated, as presented in Table 2. A1 consisted of one gateway, one hub, and one node. Two reports were expected in each round: one hub report and one node report forwarded through the hub. A2 consisted of one gateway, two hubs, and two nodes, with each hub serving one associated node. Four reports were

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therefore expected in each round.

B1 consisted of one central gateway and two report sources that communicated directly with the gateway. B2 consisted of one central gateway and four direct report sources. B1 and B2 represented the single-hop architecture with report-source counts equivalent to those of A1 and A2, respectively.

Table 2. Experimental scenarios

Scenario	Architecture	Gateway	Hub	Node/report source	Reports per round	Rounds
A1	Hierarchical multi-hub	1	1	1	2	30
A2	Hierarchical multi-hub	1	2	2	4	30
B1	Single-hop multi-node	1	–	2	2	30
B2	Single-hop multi-node	1	–	4	4	30

Each scenario was tested at nominal distances of 10, 50, and 100 m. The nominal distance represented the separation between the gateway and the remote device group. In the multi-hub scenarios, the gateway, hub, and node were positioned along the same line, while each hub and its associated node were separated by a fixed distance of 3 m. This arrangement maintained the node-to-hub connection as a local link, while the hub-to-gateway connection represented the link to the central data collector. The device configuration, polling mechanism, number of rounds, and placement conditions were maintained across the three test distances.

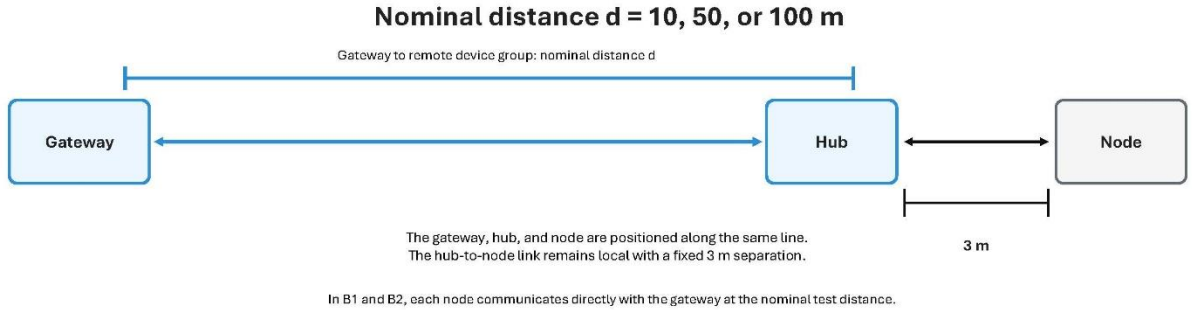


Figure 2. Device arrangement at nominal test distances of 10, 50, and 100 m

Figure 2 illustrates the physical arrangement used to define the nominal test distance. The nominal distance (d), set to 10, 50, or 100 m, represents the separation between the gateway and the remote device group. In the multi-hub configurations, the gateway, hub, and associated node were positioned along the same line, while the hub-to-node separation was maintained at 3 m. This arrangement kept the node-to-hub communication as a local link and allowed the hub-to-gateway link to represent the distance-dependent communication path. In the single-hop multi-node configurations, each node communicated directly with the gateway at the corresponding nominal test distance. This placement was maintained consistently across the experimental scenarios to support a controlled comparison between the two architectures.

Experimental Procedure

Before each test, the architecture scenario, nominal distance, and number of rounds were configured at the gateway. The gateway then created a CSV file for storing the experimental records. At the beginning of each round, the gateway initiated the data collection procedure according to the selected architecture.

In the multi-node scenarios, the gateway sequentially transmitted a request to each report source. A source transmitted its report directly to the gateway after receiving the request. In the multi-hub scenarios, the gateway sequentially transmitted requests to the hubs. Each hub first collected a report from its associated node and subsequently transmitted the hub and node reports to the gateway.

When an expected response was not received within the predefined waiting period, one retry was performed. If no response was received after the retry, the event was recorded as a TIMEOUT. After all sources or hubs had been processed, the gateway recorded a ROUND_DONE event together with the round completion time and completion status. This procedure was repeated until 30 rounds had been completed for each combination of architecture and distance.

The recorded fields included the timestamp, scenario, distance, round identifier, event type, source device, destination device, communication link, RSSI, round time, and communication status. The original experimental records were retained without modification. Event filtering and performance metric calculations were conducted during the data analysis stage.

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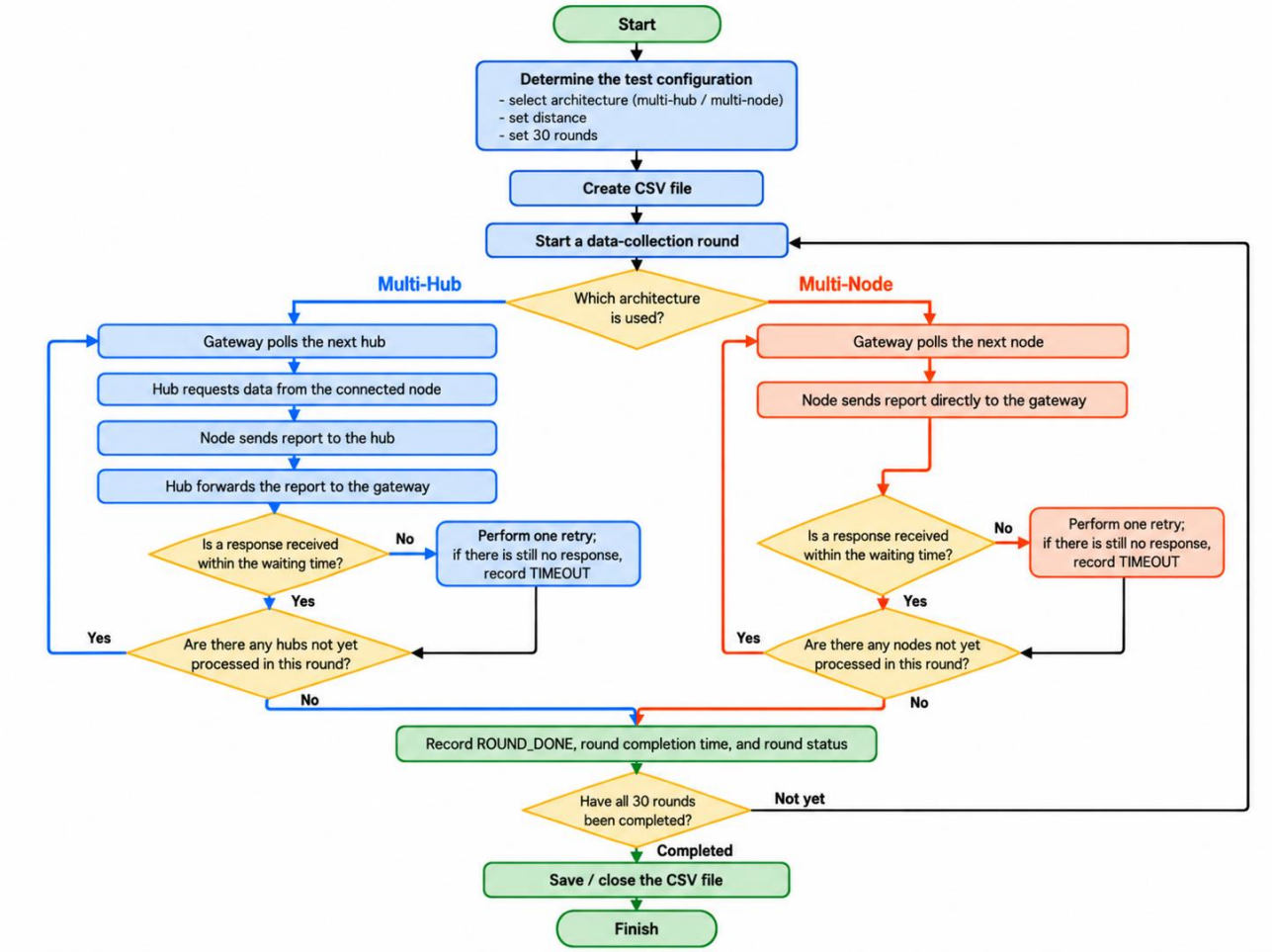


Figure 3. Experimental procedure for multi-hub and multi-node data collection

Figure 3 summarizes the complete experimental procedure for both communication architectures. Each test begins by configuring the selected architecture, nominal distance, and 30 data-collection rounds, followed by the creation of a CSV data file. In the multi-hub architecture, the gateway sequentially polls each hub, the hub requests data from its associated node, and the collected reports are then forwarded to the gateway. In the multi-node architecture, the gateway sequentially polls each node, which responds directly to the gateway. If a response is not received within the predefined waiting period, one retry is performed; if no response is obtained after the retry, a TIMEOUT event is recorded. The procedure continues until all hubs or nodes in the current round have been processed. The gateway then records the ROUND_DONE event, round completion time, and round status. The same procedure is repeated until all 30 rounds have been completed, after which the CSV data file is closed and stored for subsequent analysis.

Performance Metrics

The report delivery ratio (PDR) was used to measure the proportion of received reports relative to the number of reports planned for a scenario. The number of expected reports was determined from the number of report sources and the number of test rounds. PDR was calculated using (1).

$$PDR = \frac{N_{\text{report}}}{N_{\text{round}} \times N_{\text{source}}} \times 100\% \quad (1)$$

where N_{report} is the number of successfully received REPORT events, N_{round} is the number of planned rounds, and N_{source} is the number of report sources in the scenario.

RSSI was used to evaluate the received signal strength of gateway-facing communication links. To compare equivalent link types, the primary RSSI analysis included only REPORT events for which the gateway was the destination. In A1 and A2, these observations represented the hub-to-gateway links. In B1 and B2, they represented the node-to-gateway links. Node-to-hub RSSI was treated separately as a characteristic of the local hierarchical link and was not included in the primary architectural comparison.

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Round completion time was defined as the time required to complete one data collection cycle. Its value was obtained from round_time_ms in each ROUND_DONE event. The arithmetic mean and sample standard deviation were calculated to describe the central tendency and round-to-round variation. The mean round completion time was calculated using (2), and the sample standard deviation was calculated using (3).

$$\bar{T} = \frac{1}{n}\sum_{i=1}^{n} T_i \qquad (2)$$

$$s_T = \sqrt{\frac{\sum_{i=1}^{n}(T_i - \bar{T})^2}{n-1}} \qquad (3)$$

where T_i is the completion time of round i, $\bar{T}$ is the mean round completion time, and n is the number of observed rounds.

Timeout performance was determined from the number of TIMEOUT events recorded during the 30 rounds. Because the dataset did not explicitly record every transmitted request, a timeout-to-request ratio was not calculated. Timeout performance was therefore reported as the number of timeout events per 30 rounds.

The successful-round ratio was used to distinguish report completeness from successful completion of the entire data collection procedure. A round was classified as successful when its ROUND_DONE event had an OK status. The successful-round ratio was calculated using (4).

$$R_{\text{success}} = \frac{N_{\text{round,OK}}}{N_{\text{round,planned}}} \times 100\% \qquad (4)$$

where N_{round} is the number of ROUND_DONE events with an OK status and $N_{\text{round,planned}}$ is the number of planned rounds.

Data Analysis

The analysis was performed separately for each combination of scenario and distance. A1 was compared with B1 to evaluate hierarchical and direct communication with two report sources. A2 was compared with B2 to evaluate the same architectures with four report sources. The effect of distance was examined by comparing the results obtained at 10, 50, and 100 m within each scenario.

PDR and successful-round ratio were reported as percentages, whereas timeout performance was reported as the number of events per 30 rounds. RSSI and round completion time were summarized using the arithmetic mean and sample standard deviation. The analysis was descriptive because each scenario–distance combination was represented by one experimental session containing 30 sequential rounds. Consequently, inferential significance was not claimed. The analysis was intended to identify observed performance patterns and operational trade-offs between direct single-hop and hierarchical data collection.

RESULT

The experimental results were obtained from 12 scenario–distance combinations, with each combination consisting of 30 data collection rounds. A1 and B1 each generated 60 expected reports, whereas A2 and B2 each generated 120 expected reports. The results are presented in terms of report delivery performance, gateway-facing RSSI, round completion time, timeout events, and round completion status.

Report Delivery Performance

All reports expected from A1, A2, B1, and B2 were received at test distances of 10, 50, and 100 m. The report delivery ratio therefore reached 100% in all scenario–distance combinations. The report delivery results, successful-round counts, and timeout events are presented in Table 3.

Table 3. Report delivery, successful rounds, and timeout events

Scenario	Distance (m)	Expected reports	Received reports	PDR (%)	Successful rounds	Successful-round ratio (%)	Timeout events
A1	10	60	60	100.00	30	100.00	0
A1	50	60	60	100.00	30	100.00	0
A1	100	60	60	100.00	30	100.00	0
A2	10	120	120	100.00	29	96.67	1
A2	50	120	120	100.00	29	96.67	1
A2	100	120	120	100.00	29	96.67	1
B1	10	60	60	100.00	30	100.00	0
B1	50	60	60	100.00	30	100.00	0

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B1	100	60	60	100.00	30	100.00	0
B2	10	120	120	100.00	30	100.00	0
B2	50	120	120	100.00	30	100.00	0
B2	100	120	120	100.00	30	100.00	0

A1, B1, and B2 completed all 30 rounds with an OK status at every distance. A2 completed 29 rounds with an OK status and one round with a FAIL status at each distance. The A2 timeout events were recorded in Round 6 at 10 m, Round 9 at 50 m, and Round 2 at 100 m. All expected reports from these rounds were present in the dataset. Consequently, A2 maintained a report delivery ratio of 100%, although its successful-round ratio was 96.67%.

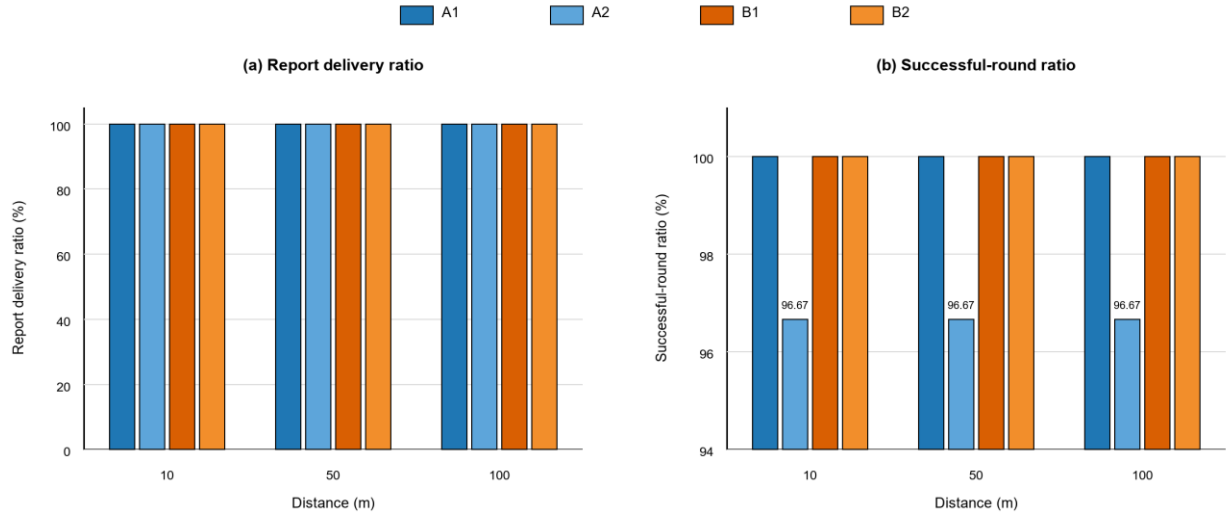


Figure 4. Report delivery ratio and successful-round ratio for each scenario and distance

RSSI of Gateway-Facing Links

The RSSI values in Table 4 include only reports received directly by the gateway. In A1 and A2, these values represent the hub-to-gateway links. In B1 and B2, they represent the node-to-gateway links. The A1 mean was calculated from 30 gateway-facing reports at each distance, whereas the A2 mean was calculated from 60 reports. The B1 and B2 means were calculated from 60 and 120 reports per distance, respectively.

Table 4. RSSI of gateway-facing links

Scenario	Distance (m)	Observations	Mean RSSI (dBm)	Standard deviation (dB)
A1	10	30	−27.77	1.33
A1	50	30	−39.33	1.06
A1	100	30	−55.63	0.96
A2	10	60	−26.92	1.03
A2	50	60	−40.32	1.32
A2	100	60	−54.72	1.99
B1	10	60	−29.12	0.98
B1	50	60	−41.57	1.32
B1	100	60	−56.17	2.01
B2	10	120	−29.86	1.68
B2	50	120	−39.64	2.54
B2	100	120	−53.36	3.75

At 10 m, the mean gateway-facing RSSI values ranged from −26.92 to −29.86 dBm. At 50 m, they ranged from −39.33 to −41.57 dBm, whereas the values at 100 m ranged from −53.36 to −56.17 dBm.

For A1, the mean RSSI changed from −27.77 dBm at 10 m to −39.33 dBm at 50 m and −55.63 dBm at 100 m. For A2, the corresponding values were −26.92, −40.32, and −54.72 dBm. The mean B1 RSSI values were −29.12, −41.57, and −56.17 dBm, whereas the B2 values were −29.86, −39.64, and −53.36 dBm.

The RSSI standard deviation ranged from 0.96 to 1.33 dB for A1, 1.03 to 1.99 dB for A2, 0.98 to 2.01 dB for B1, and 1.68 to 3.75 dB for B2. The highest RSSI standard deviation was recorded for B2 at 100 m.

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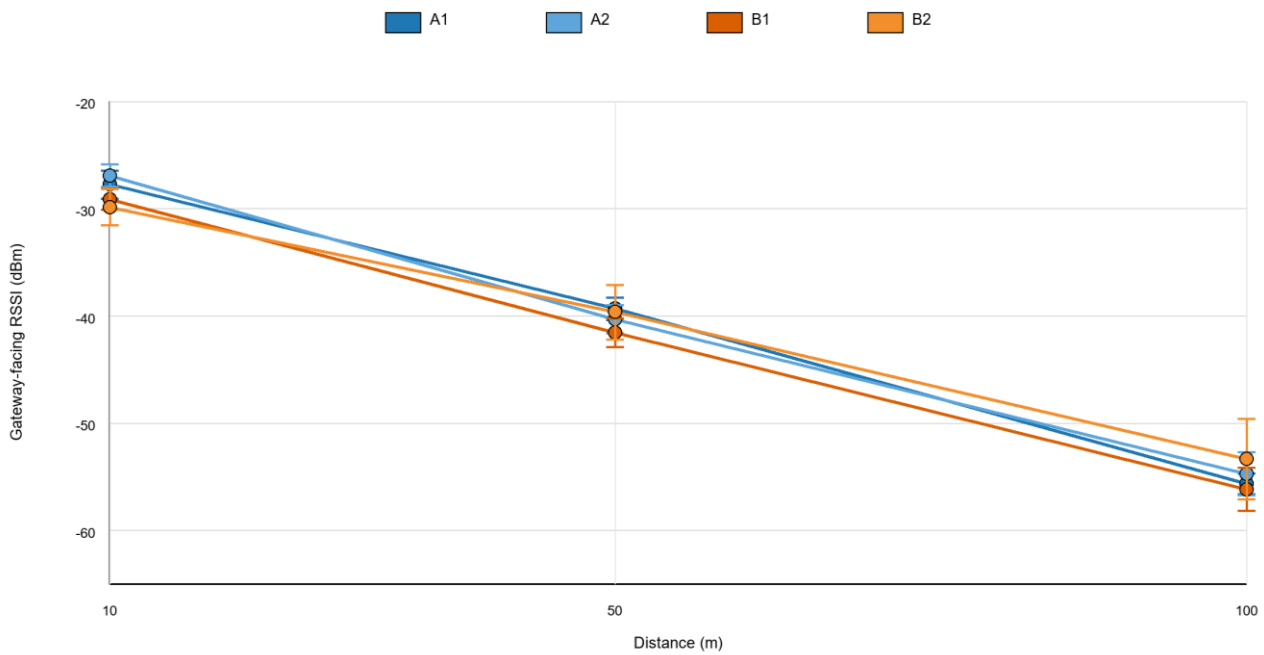


Figure 5. Mean gateway-facing RSSI at test distances of 10, 50, and 100 m

Round Completion Time

Round completion time was obtained from round_time_ms in the ROUND_DONE records. Each mean and standard deviation was calculated from 30 rounds. The round completion time results are presented in Table 5.

Table 5. Round completion time

Scenario	Distance (m)	Rounds	Mean round completion time (ms)	Standard deviation (ms)
A1	10	30	4,210.73	6.63
A1	50	30	4,221.37	6.33
A1	100	30	4,228.03	10.04
A2	10	30	9,208.40	1,380.61
A2	50	30	9,245.73	1,380.50
A2	100	30	9,252.77	1,382.05
B1	10	30	1,974.47	23.34
B1	50	30	1,969.83	23.21
B1	100	30	1,974.47	23.34
B2	10	30	3,888.73	37.82
B2	50	30	3,892.40	34.80
B2	100	30	3,896.97	40.32

B1 recorded mean round completion times ranging from 1,969.83 to 1,974.47 ms, whereas the B2 values ranged from 3,888.73 to 3,896.97 ms. For the multi-hub architecture, the A1 means ranged from 4,210.73 to 4,228.03 ms, whereas the A2 means ranged from 9,208.40 to 9,252.77 ms.

For the two-source comparison, the differences between the A1 and B1 mean round completion times were 2,236.26 ms at 10 m, 2,251.54 ms at 50 m, and 2,253.56 ms at 100 m. For the four-source comparison, the differences between A2 and B2 were 5,319.67, 5,353.33, and 5,355.80 ms at 10, 50, and 100 m, respectively.

The A1 round-time standard deviation ranged from 6.33 to 10.04 ms. The corresponding ranges were 23.21–23.34 ms for B1, 34.80–40.32 ms for B2, and 1,380.50–1,382.05 ms for A2. In the A2 rounds containing a timeout event, the recorded round completion times were 16,518 ms at 10 m, 16,541 ms at 50 m, and 16,570 ms at 100 m.

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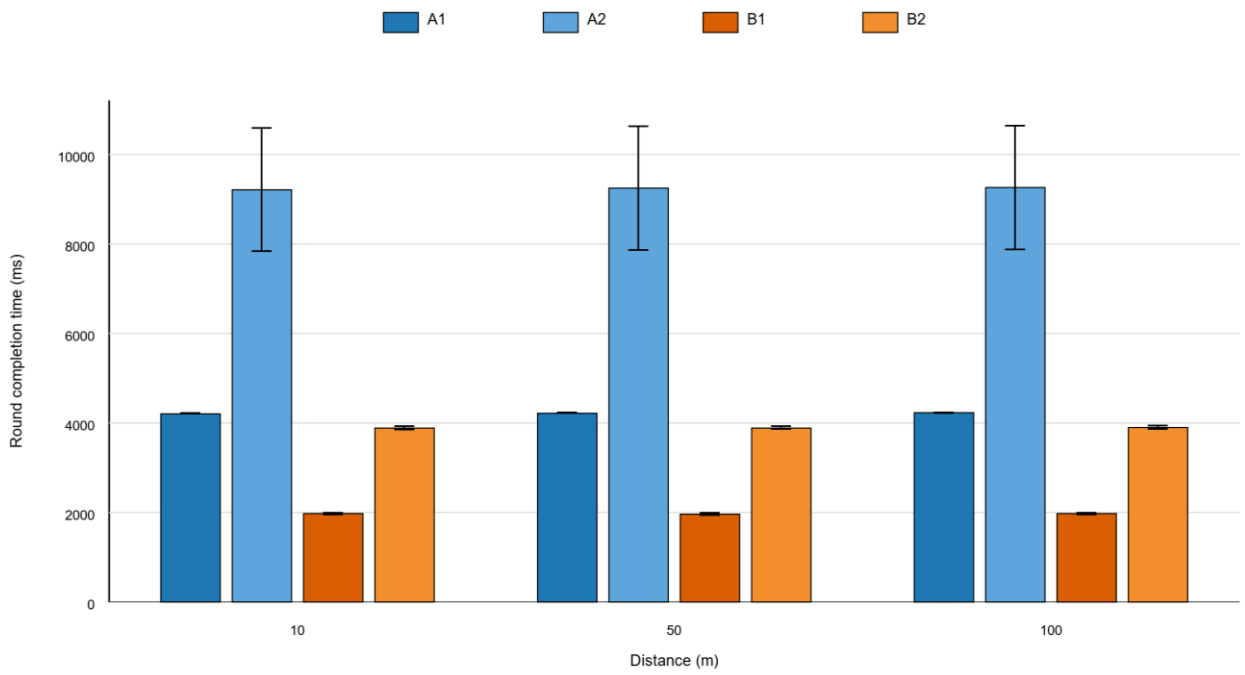


Figure 6. Mean and standard deviation of round completion time for each scenario

Comparison by Number of Report Sources

Increasing the number of report sources from two to four increased the mean round completion time in both architectures. At 10 m, the multi-hub round completion time increased from 4,210.73 ms in A1 to 9,208.40 ms in A2. At the same distance, the single-hop multi-node round completion time increased from 1,974.47 ms in B1 to 3,888.73 ms in B2.

At 50 m, the A1 and A2 mean round completion times were 4,221.37 and 9,245.73 ms, respectively, whereas the corresponding B1 and B2 values were 1,969.83 and 3,892.40 ms. At 100 m, the mean values were 4,228.03 ms for A1, 9,252.77 ms for A2, 1,974.47 ms for B1, and 3,896.97 ms for B2.

The report delivery ratio remained at 100% after the number of report sources increased from two to four. A change in the successful-round ratio was observed only in the multi-hub architecture, decreasing from 100% in A1 to 96.67% in A2. In the single-hop multi-node architecture, both B1 and B2 achieved a successful-round ratio of 100% at all test distances.

DISCUSSION

Report Delivery Reliability and Round Completion

The 100% PDR recorded in all scenarios indicates that both the multi-hub and multi-node architectures collected all expected reports at 10, 50, and 100 m. Under the tested conditions, increasing the number of report sources from two to four did not result in report loss. The sequential polling mechanism controlled the transmission order when multiple devices used the same channel and frequency. Because a device transmitted only after receiving a request, the probability of simultaneous transmissions was reduced. This result is consistent with studies on time-slotted MAC and scheduled LoRa communication, which have shown that transmission scheduling can improve channel access coordination (Alahmadi et al., 2022; Álamos et al., 2022; Fahmida et al., 2024).

Although all A2 reports were received, one of the 30 rounds at each distance had a FAIL status, resulting in a successful-round ratio of 96.67%. This finding demonstrates that report PDR and successful round completion represent different aspects of communication performance. PDR measures the completeness of the reports eventually recorded by the gateway, whereas the successful-round ratio indicates whether the complete data collection procedure was completed without exceeding the response waiting period. Evaluating PDR alone may therefore conceal timing disturbances that occur during the collection procedure.

The A2 event sequence showed that a TIMEOUT event was recorded before the corresponding hub and node reports appeared within the same round. However, the available records do not distinguish whether the reports were received following a retry or arrived after the initial waiting period. Individual request and retry events were not explicitly recorded. The observed condition is therefore reported as one timeout event per 30 rounds rather than as a timeout-to-request ratio.

No timeout was observed in B2, indicating that four direct report sources could still be served sequentially under the tested conditions. In contrast, the timeout events in A2 show that an additional communication level and multiple

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hub transactions can affect timely round completion without necessarily causing report loss. The evaluation of a hierarchical network should therefore consider both packet reception and completion of the entire data collection procedure within its expected timing sequence.

Effect of Distance on RSSI

The mean RSSI of gateway-facing links decreased in all scenarios as the test distance increased from 10 to 100 m. The RSSI decreases for A1, A2, B1, and B2 were 27.86, 27.80, 27.05, and 23.50 dB, respectively. This common pattern shows that distance affected the received signal strength of links terminating at the gateway, regardless of whether the transmitting device operated as a hub or a direct node.

At the same distance, the differences among the mean RSSI values were relatively small. At 100 m, the A1 and A2 mean RSSI values were −55.63 and −54.72 dBm, respectively, whereas the B1 and B2 values were −56.17 and −53.36 dBm. The gateway-facing link qualities of both architectures therefore remained within a similar range under the tested conditions. The substantial differences in round completion time were not accompanied by comparably large differences in gateway-facing RSSI.

The highest RSSI standard deviation, 3.75 dB, was recorded for B2 at 100 m. B2 contained four devices transmitting directly to the gateway; consequently, its aggregated RSSI statistics included variations among several devices and physical links. In contrast, A1 contained only one hub-to-gateway link and exhibited a lower RSSI standard deviation. Variation in aggregated RSSI values may therefore reflect not only the test distance but also the number and individual characteristics of the links included in the calculation.

Despite the RSSI decrease, all scenarios maintained a PDR of 100%. The RSSI levels observed at 100 m were therefore sufficient to receive all expected reports under the experimental conditions. This result establishes reliable operation up to the maximum tested distance but does not identify the communication-range limit of either architecture.

Osorio et al. (2022) showed that packet reception deteriorated under NLOS direct LoRaWAN communication, whereas the use of multi-hop routing improved packet delivery to the gateway. Strzoda and Grochla (2024) similarly considered relay devices as a solution for nodes located in coverage blind spots. Such direct-link degradation was not observed in B1 or B2 because both scenarios maintained a PDR of 100%. The present results therefore demonstrate the availability of a hierarchical forwarding structure but do not provide empirical evidence that the multi-hub architecture achieves a greater maximum range than direct multi-node communication.

Communication Overhead of the Hierarchical Architecture

The clearest difference between the architectures was observed in round completion time. With two report sources, the A1 round completion time was approximately 2.13–2.15 times that of B1. With four report sources, the A2 round completion time was approximately 2.37 times that of B2. These differences quantify the additional communication overhead introduced by the multi-hub architecture.

In the multi-node architecture, each transaction consisted of a gateway polling request followed by a direct node response. In the multi-hub architecture, each data collection sequence included gateway-to-hub polling, a hub-to-node request, a node-to-hub response, and transmission of the collected reports from the hub to the gateway. The additional node-to-hub exchange, local data collection, and forwarding operations increased the time required to complete one round.

This result is consistent with the characteristics of multi-hop LoRa networks discussed by Wong et al. (2024), in which intermediate forwarding provides greater topological flexibility but introduces accumulated delay. The analytical model presented by Alhomyani et al. (2024) also showed that multi-hop operation may provide capacity and throughput advantages in a linear network while increasing network traffic and potential congestion. In the present experiment, the effect of the additional communication stages was observed as an increase in round completion time.

García et al. (2025) reported latency values between 0.5 and 3.2 s in a hybrid star-and-mesh implementation. These values cannot be directly compared with the present measurements because of differences in protocol operation, network size, radio configuration, channel access mechanism, and latency definition. Nevertheless, both studies indicate that an indirect communication path can provide additional connectivity functions at the cost of extra communication time.

The effect of distance on round completion time was considerably smaller than the effect of architecture. From 10 to 100 m, the A1 mean increased by only 17.30 ms, corresponding to approximately 0.41%. The A2 mean increased by 44.37 ms, or approximately 0.48%, whereas the B2 mean increased by 8.24 ms, or approximately 0.21%. The B1 means remained nearly unchanged across the three distances. Within the tested range, round completion time was therefore more strongly associated with the number and sequence of communication transactions than with distance.

Effect of Increasing the Number of Report Sources

Increasing the number of report sources from two to four increased the mean round completion time in both architectures. In the single-hop architecture, the transition from B1 to B2 approximately doubled the round completion time. This pattern corresponds to the sequential polling procedure because each additional source requires another

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gateway request and response transaction.

In the hierarchical architecture, the transition from A1 to A2 increased the round completion time by more than two times. In addition to the greater number of reports, A2 required two node-to-hub collection procedures and two hub-to-gateway transactions. The timeout event observed in each A2 test also increased its mean round completion time and standard deviation. The rounds containing a timeout required approximately 16.52–16.57 s, considerably longer than the other rounds.

The A2 round-time standard deviation of approximately 1.38 s shows that a single timeout round strongly affected the overall temporal variation. In contrast, A1 recorded standard deviations of only 6.33–10.04 ms and contained no timeout events. Increasing the number of hubs therefore not only extended the cycle duration but also increased the effect of a delayed response on round-time consistency under the tested configuration.

Sequential gateway control maintained a 100% report PDR as the number of sources increased. However, the round-time measurements show that serving more devices through sequential polling increases the duration of the data collection cycle. This reliability–delay trade-off is also relevant to real-time and TDMA-based LoRa protocols, which seek to coordinate channel access while limiting accumulated waiting time (Fahmida et al., 2024; Beletsioti et al., 2025; Sahoo et al., 2025).

Architectural Implications

The results indicate that the single-hop multi-node architecture is more suitable when all devices can maintain adequate direct links with the gateway and short data collection time is the primary requirement. At equivalent report-source counts, direct communication produced lower round completion times and a successful-round ratio of 100%. It also required no intermediate collection or forwarding process.

The multi-hub architecture provides a different function. Each node communicates with its associated hub over a local 3 m link, and the hub subsequently forwards the reports to the gateway. This structure separates the network into node, hub, and gateway levels. Its measured cost is a longer round completion time because each data collection cycle contains additional communication stages. Therefore, the demonstrated benefit of the multi-hub architecture is not a higher PDR, because all scenarios achieved the same PDR, but the availability of a hierarchical data collection structure.

Architectural selection should not be based on a single metric. PDR represents report completeness, the successful-round ratio represents timely procedural completion, RSSI describes gateway-facing link conditions, and round completion time quantifies the temporal cost of the communication structure. When all nodes have adequate direct connectivity, the multi-node architecture provides faster data collection. When direct gateway connectivity is unavailable or unreliable, an intermediate hub may provide an alternative forwarding path, as reported in previous relay and multi-hop studies (Osorio et al., 2022; Strzoda & Grochla, 2024; García et al., 2025).

Study Limitations

The experiment used a limited number of devices, with a maximum of two hubs and two associated nodes in the multi-hub architecture and four direct nodes in the multi-node architecture. Each scenario–distance combination was represented by one experimental session containing 30 rounds. The results were therefore analyzed descriptively and were not used to claim inferential statistical significance across independent experimental populations.

The maximum test distance was 100 m, at which all scenarios still achieved a PDR of 100%. Consequently, the communication-range limit and the point at which direct communication begins to experience report loss could not be determined. The frequency, air data rate, output power, and sub-packet configuration were also kept constant, and their individual effects were not evaluated.

Environmental conditions, channel interference, and propagation characteristics were not recorded as measured variables. Request and retry transmissions were not logged as separate events, preventing the calculation of a timeout-to-request ratio. In addition, the power consumption of the gateway, hubs, and nodes was not measured. These limitations restrict the discussion to PDR, gateway-facing RSSI, round completion time, timeout events per 30 rounds, and successful round completion under the experimental conditions used in this study.

CONCLUSION

This study experimentally compared hierarchical multi-hub and single-hop multi-node LoRa architectures under equivalent report-source counts, radio configurations, test distances, and numbers of data collection rounds. Both architectures achieved a report delivery ratio of 100% at 10, 50, and 100 m. Increasing the number of report sources from two to four did not result in report loss. However, the successful-round ratio of A2 was 96.67% because one timeout and one failed round were recorded at each distance, whereas A1, B1, and B2 completed all rounds successfully.

The principal difference between the architectures was their round completion time. The mean completion time ranged from 1,969.83 to 1,974.47 ms for B1 and from 3,888.73 to 3,896.97 ms for B2. The corresponding multi-hub values ranged from 4,210.73 to 4,228.03 ms for A1 and from 9,208.40 to 9,252.77 ms for A2. These results show that

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direct single-hop communication completed data collection more rapidly, whereas hierarchical communication required additional time for node-to-hub collection and hub-to-gateway forwarding. Distance had a smaller effect on round completion time than the communication architecture and number of report sources.

The gateway-facing RSSI decreased as the distance increased, but this reduction did not result in report loss within the tested range. Consequently, the results demonstrate reliable operation up to 100 m but do not establish the maximum communication range of either architecture. The multi-node architecture is suitable when all nodes have reliable direct connectivity and low collection time is required. The multi-hub architecture provides a structured hierarchical data collection path when intermediate collection is required, although it introduces additional communication overhead.

The study was limited to four report sources, one experimental session of 30 rounds for each scenario–distance combination, fixed radio parameters, and a maximum test distance of 100 m. Further studies should evaluate larger device populations, independent experimental repetitions, longer distances, different radio and payload configurations, explicit request and retry logging, environmental and interference conditions, and device-level energy consumption. These extensions are required to determine the scalability, communication-range limits, and energy–delay trade-offs of both architectures.

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REFERENCES

Alahmadi, H., Bouabdallah, F., & Al-Dubai, A. (2022). A novel time-slotted LoRa MAC protocol for scalable IoT networks. *Future Generation Computer Systems, 134*, 287–302. https://doi.org/10.1016/j.future.2022.04.003

Alhomyani, H., Fadel, M., Dimitriou, N., Bakhsh, H., & Aldabbagh, G. (2024). Modeling the performance of a multi-hop LoRaWAN linear sensor network for energy-efficient pipeline monitoring systems. *Applied Sciences, 14*(20), Article 9391. https://doi.org/10.3390/app14209391

Álamos, J., Kietzmann, P., Schmidt, T. C., & Wählisch, M. (2022). DSME-LoRa: Seamless long-range communication between arbitrary nodes in the constrained IoT. *ACM Transactions on Sensor Networks, 18*(4), Article 69, 1–43. https://doi.org/10.1145/3552432

Asteriou, V., Valkanis, A., Beletsioti, G., Kantelis, K., Papadimitriou, G., & Nicopolitidis, P. (2022). LoRaWAN-based adaptive MACs for event response applications. *IEEE Access, 10*, 97465–97480. https://doi.org/10.1109/ACCESS.2022.3204654

Banti, K., Karampelia, I., Dimakis, T., Boulogeorgos, A.-A. A., Kyriakidis, T., & Louta, M. (2022). LoRaWAN communication protocols: A comprehensive survey under an energy efficiency perspective. *Telecom, 3*(2), 322–357. https://doi.org/10.3390/telecom3020018

Beletsioti, G. A., Kantelis, K. F., Valkanis, A., Nicopolitidis, P., Papadimitriou, G. I., & Louta, M. (2025). Gateway energy-oriented TDMA for LoRa networks. *Electronics, 14*(22), Article 4496. https://doi.org/10.3390/electronics14224496

Fahmida, S., Jain, A., Modekurthy, V. P., Ismail, D., & Saifullah, A. (2024). RTPL: A real-time communication protocol for LoRa network. *ACM Transactions on Embedded Computing Systems, 24*(1), Article 17, 1–31. https://doi.org/10.1145/3702209

García, L., Cancimance, C., Asorey-Cacheda, R., Zúñiga-Cañón, C.-L., García-Sánchez, A.-J., & García-Haro, J. (2025). Compliant and seamless hybrid (star and mesh) network topology coexistence for LoRaWAN: A proof of concept. *Applied Sciences, 15*(7), Article 3487. https://doi.org/10.3390/app15073487

Li, C., & Cao, Z. (2022). LoRa networking techniques for large-scale and long-term IoT: A down-to-top survey. *ACM Computing Surveys, 55*(3), Article 52, 1–36. https://doi.org/10.1145/3494673

Osorio, A., Calle, M., Soto, J., & Candelo-Becerra, J. E. (2022). Routing in LoRa for smart cities: A gossip study. *Future Generation Computer Systems, 136*, 84–92. https://doi.org/10.1016/j.future.2022.05.028

Ridho, S., Dahlan, A. A., Yustini, Y., Rusfandi, R., & Ferdiansyah, F. (2025). Evaluasi kinerja eksperimental mekanisme Gateway-Polled Sequential Access (GPSA) pada jaringan LoRa multi-node single-hop untuk aplikasi Internet of Things (IoT). *Jurnal Teknologi, 25*(3), 258–271. https://doi.org/10.30811/teknologi.v25i3.8301

Sahoo, S. R., Gamage, A., Kumar, N., & Easwaran, A. (2025). LoRaHART: Hardware-aware real-time scheduling for LoRa. In R. Mancuso (Ed.), *37th Euromicro Conference on Real-Time Systems (ECRTS 2025)* (Leibniz International Proceedings in Informatics, Vol. 335, Article 10, pp. 10:1–10:28). Schloss Dagstuhl–Leibniz-Zentrum für Informatik. https://doi.org/10.4230/LIPIcs.ECRTS.2025.10

Strzoda, A., & Grochla, K. (2024). A nature-inspired approach to energy-efficient relay selection in low-power wide-area networks (LPWAN). *Sensors, 24*(11), Article 3348. https://doi.org/10.3390/s24113348

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Research of Artificial Intelligence

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https://doi.org/10.47709/brilliance.v6i4.9632

Sun, Z., Yang, H., Liu, K., Yin, Z., Li, Z., & Xu, W. (2022). Recent advances in LoRa: A comprehensive survey. *ACM Transactions on Sensor Networks, 18*(4), Article 67, 1–44. https://doi.org/10.1145/3543856

Wong, A. W.-L., Goh, S. L., Hasan, M. K., & Fattah, S. (2024). Multi-hop and mesh for LoRa networks: Recent advancements, issues, and recommended applications. *ACM Computing Surveys, 56*(6), Article 136, 1–43. https://doi.org/10.1145/3638241

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